The Galactic centre mini-spiral with CARMA

D Kunneriath[1], A Eckart[2,3], S N Vogel[4], P Teuben[4], K Mužić[5], R Schödel[6], M García-Marín[2], J Moultaka[7], J Staguhn[4,8,9], C Straubmeier[2], J A Zensus[3,2], M Valencia-S[2,3], V Karas[1]

[1] Astronomical Institute, Academy of Sciences, Boční II 1401, CZ-14100 Prague, Czech Republic
[2] I.Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[4] Department of Astronomy, University of Maryland, College Park, MD 20742-2421, USA
[5] Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Str., Toronto ON M5S 3H4, Canada
[6] Instituto de Astrofísica de Andalucía - CSIC, Glorieta de la Astronomía S/N, 18008, Spain
[7] LATT, Université de Toulouse, CNRS, 14, Avenue Edouard Belin, 31400 Toulouse, France
[8] NASA Goddard Space Flight Ctr., Greenbelt, MD 20771, USA
[9] Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

E-mail: devaky@astro.cas.cz

Abstract. The Galactic centre mini-spiral region is a mixture of gas and dust with temperatures ranging from a few hundred K to 10^4 K. We report results from 1.3 and 3 mm radio interferometric observations of this region with CARMA, and present a spectral index map of this region. We find a range of emission mechanisms in the region, including the inverted synchrotron spectrum of Sgr A*, free-free emission from the mini-spiral arms, and a possible dust emission contribution indicated by a positive spectral index.

1. Introduction

The central region of the centre of our Galaxy, the Milky Way, is dominated by the non-thermal emission from Sgr A*, the supermassive black hole of mass $\sim 4\times10^6\,M_\odot$ [1, 2, 3], the interstellar medium of the Circumnuclear Disk (CND) and the mini-spiral, and the nuclear stellar cluster.

The mini-spiral is believed to be a superposition of infalling streams of gas and dust from the CND, an association of molecular gas and dust of mass $\sim 10^5\,M_\odot$ [4] extending from 1.5 pc to about 4–7 pc. The infalling streams are ionized by the stars and Sgr A* in the central parsec. The main features of the mini-spiral are the Northern Arm, Western Arc, Eastern Arm and the Bar, which are believed to be in Keplerian orbits around the central SMBH, with some significant deviations possibly caused by stellar winds [5, 6]. The radio emission from the region is dominated by the thermal emission of the ionized gas from the mini-spiral arms, while the near-infrared (NIR) bands are dominated by the stellar sources. The mid-infrared (MIR) is dominated by dust emission at $\sim$200 K [7], resulting in a mixture of dust and gas with temperatures ranging from a few hundred K from the dust to up to 10^4 K radio bremsstrahlung plasma in this region.

Radio interferometric observations are a useful tool to separate the emission of Sgr A* from the surrounding mini-spiral, especially at higher frequencies with reasonably high resolution (∼2″). In order to understand the emission mechanisms dominating the central parsec region of the Galaxy and to derive some of the physical characteristics of the medium, such as number density, emission measure, etc., we analysed the region at multiple wavelengths, ranging from the NIR to MIR to radio mm wavelengths. The results are presented in [8, 9]. In this paper, we present a subset of those observations, namely the radio mm observations and the spectral index map produced at these wavelengths.

2. Observations

We observed the Galactic centre region with the Combined Array for Research in mm-wave Astronomy (CARMA)[1] at 1.3 mm (230 GHz) with the C and D array configuration and at 3 mm (100 GHz) with the C configuration. The array consists of 15 telescopes, with six 10.4 m telescopes and nine 6.1 m telescopes, with five array cconfigurations, A to E, with baselines ranging from 0.25–2 km to 8–66 m, respectively. Fig.1 shows the D configuration 1.3 mm map of the central 1.5 pc (40″).

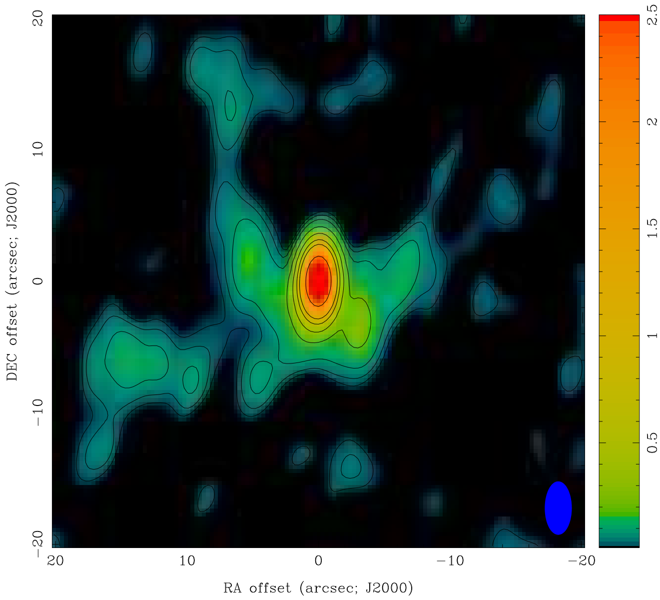

Figure 1. 1.3 mm map of the mini-spiral region at resolution 4.0″ by 2.0″ (P.A=0°). Contour levels are 0.02, 0.04, 0.08, 0.2, 0.4, 0.7, 1.0, 2.0 Jy/beam.

3. Results and Discussion

The spectral index map of the central 1.5 pc of the GC produced using the 1.3 mm and 3 mm maps convolved to the same angular resolution of 4″×2″ (P.A.=0°) is shown in Fig.2.

We obtained a spectral index of ∼0.5 for Sgr A*, which indicates an inverted synchrotron spectrum, in agreement with previously published results [10, 11]. From the ionized gas in the mini-spiral arms we expect optically thin bremsstrahlung radiation with a spectral index of

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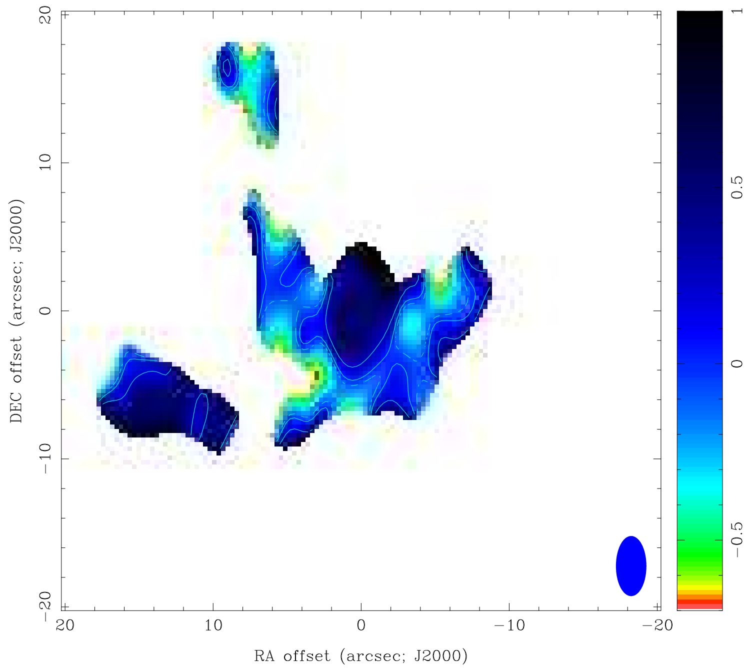

Figure 2. Spectral index map obtained from 1.3 mm and 3 mm, beam size $4'' \times 2''$ (P.A.=0°). Contour levels indicate spectral indices of -0.1 (dashed), 0.4 and 1.0.

$\sim$0.1, which is observed in most of the mini-spiral but with some exceptions. The Northern Arm shows steeper spectral index values $\sim$-0.5, which are generally associated with optically thin synchrotron emission, but in this case they could be the result of resolved out flux at 1.3 mm.

We also obtained positive spectral index values of $\sim$1 around the edges of the Bar and most of the Easterm Arm. At 3 mm, the mini-spiral radiation is believed to consist of mainly free-free emission. Using this assumption, we scaled our 3 mm map to 1.3 mm using the spectral index notation (S$\sim\nu^{-0.1}$), and subtracted this scaled map from our 1.3 mm map. As the bright Sgr A* dominates the spectral index in the central region, we masked the central region to exclude the emission from Sgr A*. The resultant residual map (Fig. 3) shows evidence for excess emission (compared to Bremsstrahlung) in the regions corresponding to positive spectral index regions in the spectral index map, the Eastern Arm, parts of the Bar, and a portion of the Northern Arm, which we attribute to dust emission which begins to be important at wavelengths $\leq$ 1 mm.

3.1. Uncertainty in Spectral Index

Radio interferometric maps are sensitive to the brighter emission from the compact components of the mini-spiral, and miss out on the large scale diffuse emission seen by single dish telescopes. In order to minimize effects from missing flux due to differences in uv-coverage, we have produced the spectral index map using data from array configurations which have a similar uv-coverage. The D configuration at 1.3 mm has an angular resolution of $2.18''$ at 11 m to $29.74''$ at 150 m, while the C configuration at 3 mm has an angular resolution of $2.16''$ at 30 m to $25.16''$ at 350 m. Thus we ensure that the effects of missing flux at short spacings are similar at 1.3 mm and 3 mm. Furthermore, the total flux measured by the CARMA map at 3 mm ($\sim$13 Jy) is in perfect agreement with previously published interferometric maps of the region [12, 13]. As a result it is conceivable to assume that both bands trace the same emission from the brighter small-scale features of the mini-spiral. Hence we are confident in the reliability of the spectral indices derived from these maps. There are two main aspects of the spectral index information: the emission

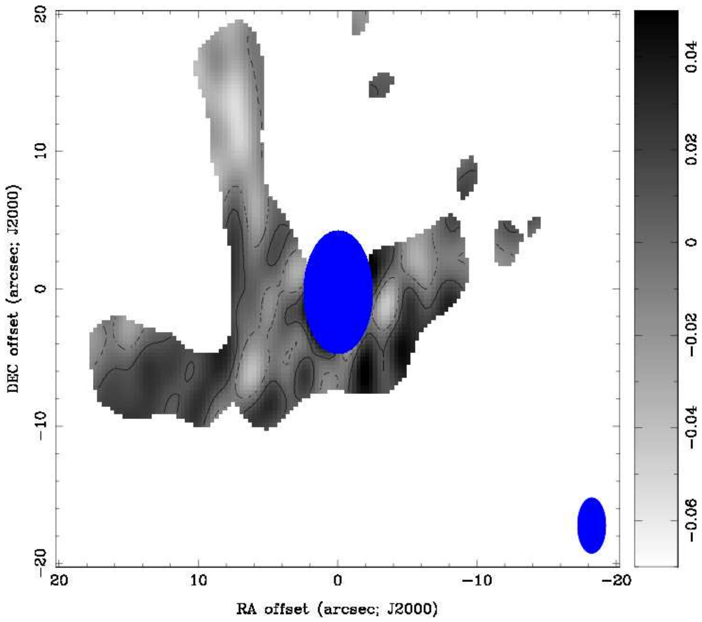

Figure 3. 1.3 mm excess emission (compared to Bremsstrahlung) at a resolution of $4'' \times 2''$ (P.A.=0°). See text for details of subtraction of free-free emission. The contour levels represent -0.01,0.01 and 0.05 Jy/beam.

mechanisms in the region, and resolution effects at different frequencies. The median spectral index obtained from the bright mini-spiral arms is ∼-0.1, indicating the dominance of free-free emission. If the radio maps suffered from resolution effects, we would see steeper spectral index values, which are not observed, except in the case of the Northern Arm, and around the edges of the mini-spiral.

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4. References

[1] Eckart A and Genzel R 1996 *Nature* **383** 415–417
[2] Schödel R, Ott T, Genzel R, Hofmann R, Lehnert M, Eckart A, Mouawad N, Alexander T, Reid M J, Lenzen R, Hartung M, Lacombe F, Rouan D, Gendron E, Rousset G, Lagrange A, Brandner W, Ageorges N, Lidman C, Moorwood A F M, Spyromilio J, Hubin N and Menten K M 2002 *Nature* **419** 694–696 (*Preprint* `arXiv:astro-ph/0210426`)
[3] Ghez A, Morris M, Lu J, Weinberg N, Matthews K, Alexander T, Armitage P, Becklin E, Brown W, Campbell R, Do T, Eckart A, Genzel R, Gould A, Hansen B, Ho L, Lo F, Loeb A, Melia F, Merritt D, Milosavljevic M, Perets H, Rasio F, Reid M, Salim S, Schödel R and Yelda S 2009 *astro2010: The Astronomy and Astrophysics Decadal Survey* (*Astronomy* vol 2010) p 89

[4] Christopher M H, Scoville N Z, Stolovy S R and Yun M S 2005 *ApJ* **622** 346–365 (*Preprint* `arXiv:astro-ph/0502532`)
[5] Zhao J H, Morris M R, Goss W M and An T 2009 *ApJ* **699** 186–214 (*Preprint* `0904.3133`)
[6] Zhao J H, Blundell R, Moran J M, Downes D, Schuster K F and Marrone D P 2010 *ApJ* **723** 1097–1109 (*Preprint* `1009.1401`)
[7] Cotera A, Morris M, Ghez A M, Becklin E E, Tanner A M, Werner M W and Stolovy S R 1999 *The Central Parsecs of the Galaxy* (*Astronomical Society of the Pacific Conference Series* vol 186) ed H Falcke, A Cotera, W J Duschl, F Melia, & M J Rieke p 240
[8] Kunneriath D, Eckart A, Zamaninasab M, Witzel G, Schödel R, García-Marín M, König S, Krichbaum T P, Lu R, Moultaka J, Mužić K, Sabha N, Sjouwerman L O, Straubmeier C, Vogel S N, Teuben P and Zensus J A 2011 *Astronomical Society of the Pacific Conference Series* (*Astronomical Society of the Pacific Conference Series* vol 439) ed M R Morris, Q D Wang, & F Yuan p 327
[9] Kunneriath D, Eckart A, Vogel S N, Teuben P, Mužić K, Schödel R, García-Marín M, Moultaka J, Staguhn J, Straubmeier C, Zensus J A, Valencia-S M and Karas V 2012 *A&A* **538** A127 (*Preprint* `1201.2362`)
[10] Yusef-Zadeh F, Roberts D, Wardle M, Heinke C O and Bower G C 2006 *ApJ* **650** 189–194 (*Preprint* `arXiv:astro-ph/0603685`)
[11] Falcke H, Goss W M, Matsuo H, Teuben P, Zhao J and Zylka R 1998 *ApJ* **499** 731 (*Preprint* `arXiv:astro-ph/9801085`)
[12] Shukla H, Yun M S and Scoville N Z 2004 *ApJ* **616** 231–246 (*Preprint* `arXiv:astro-ph/0408136`)
[13] Wright M C H, Genzel R, Güsten R and Jaffe D T 1987 *The Galactic Center* (*American Institute of Physics Conference Series* vol 155) ed D C Backer pp 133–137